

Preface

Design is one of the intellectual activities that have played a fundamental role in creating and shaping the modern civilization. Design begins with the identification of the *need* that must be satisfied and ends with an *innovation*. This translation of the need to a final solution is the responsibility and domain of a designer. The goal is to create a design that satisfies the perceived needs as specified by functional requirements (FRs) within specified constraints. How we perform this task well is the main subject addressed in this book.

Since the Industrial Revolution, major scientific discoveries and technological innovations have enabled humans to harness energy, transport people and goods, generate wealth, secure health and security, and explore the universe. All of these advances were possible because of the human ability to design and innovate. Without these advances, the world would not have had the means of supporting its rapidly expanding population and improving the quality of life at the same time. Innovations will continue to be important in the twenty-first century as we now have new challenges: global warming, sustainability, and securing peace throughout the world. Our ability to design well will continue to affect all of these important issues.

Through design, we create things and artifacts. Some designs are purely artistic. Others are technological or organizational or scientific. Some designs may involve large intelligent systems that exceed human capability. Some are in the form of algorithms that perform pre-set routines to deliver solutions to a class of common problems. To solve these challenging problems of the twenty-first century, we need to advance the field of design.

While there are many approaches to design, this book deals with the design from the perspective of Axiomatic Design (AD). The goal is to advance the “science of design” to solve practical problems by creating the foundation for “design thinking”. The innovations created based on AD share two common characteristics: simplicity and reliability of the final product. Simplicity and reliability represent the dual nature of creative design. When the design is simple, the development of the product or the system tends to take short time, and the product tends to be more reliable. These are the foundations of the two design axioms.

The idea that we should create *design science* to strengthen the discipline of design and manufacturing came out of necessity. In the late 1970s, when MIT launched a new effort for the field of design and manufacturing, we chose the creation of the science base for design and manufacturing as the ultimate goal of the Laboratory for Manufacturing and Productivity (LMP). With the generous support of the U.S. National Science Foundation (NSF), MIT embarked on AD research. A few years later, NSF created a research support program in design, which generated a cadre of young design specialists, who are now leading scholars and practitioners of the design field. Since then, much has been achieved as indicated by the chapters written by many authors of this book attest, but we still have much more to do in order to merge the scientific quest and the industrial practice so that they are indistinguishable to the scholars and the practitioners of design.

As will be discussed in greater length in Chap. 1, one defining characteristic of twenty-first century challenges is the breadth of their scope. The twentieth century was marked by several transformative technologies such as the generator, telephone, and automobile. Now, the twenty-first century arrives to address the large complex systems which have formed around these individual innovations. Our power grid, communication infrastructure, and transportation systems are all integral parts of daily life and its twenty-first century challenges. Indeed, the trends towards integrating renewable energy and smart buildings, spanning the digital divide, and electrifying transportation are all design efforts to solve today's large-scale problems.

In order to solve these broad scope challenges, design science must continue to advance beyond individual products to large complex systems. This means revisiting and potentially setting aside several limiting constraints and assumptions. First, these large complex systems span the traditional boundaries of individual engineering disciplines and so must design science seek to integrate this knowledge into a consistent framework. Second, these large complex systems rarely have one engaged "customer" but rather a diversity of internal and external stakeholders. Consequently, large complex systems have a mix of soft and hard requirements rather than a single fixed contract.

While these broad twenty-first century challenges will likely remain as such for decades and cannot be addressed within a single volume, this book seeks to advance AD as a design science specifically towards this purpose. To support this goal, the book addresses three application domains of greater scope than traditional products but more tractable than the grand challenges of the century. These three domains are large complex products, buildings, and manufacturing systems. Together, these three domains exhibit many of the previously mentioned characteristics of large complex systems while still remaining grounded as current engineering design problems. Consequently, this book is organized as follows. Part I of the book provides introductory material common to all the applications found in the book.

- Chapter 1 provides an engineering system's introduction to AD. It introduces the fundamentals of AD within the context of large complex engineering

systems and existing efforts in model-based systems engineering. It also highlights several areas where AD has made many contributions to large complex systems: quantitative measures of life cycle properties, design of cyber-physical systems, and design of hetero-functional networks.

- Chapter 2 provides a mathematical exposition of AD focusing specifically on the quantitative implications of the Independence and Information Axioms.

Part II of the book shifts the focus to address large complex products specifically:

- Chapter 3 addresses new development to guide strategic product design and systematic innovation. In particular, it explains the Linearity Theorem that guides product designers to select design parameters and drive innovation.
- Chapter 4 provides several considerations of information and complexity in AD. In particular, it provides a taxonomy of information and analyzes how each affects the progression of design.
- Chapter 5 provides a novel approach for AD for the environment. It proposes a conceptual framework for a smart eco-design platform that integrates information across AD multiple-design domains.

Part III of the book shifts the focus to address buildings specifically:

- Chapter 6 provides a literature review of the application of AD to the built environment.
- Chapter 7 applies AD to prefabricated buildings. It provides a special attention to the robustness and flexibility in the conceptual design phase.
- Chapter 8 applies AD to temporary housing with the application to refugee populations. It uses a methodology that integrates Quality Function Deployment (QFD) and AD to tie stakeholder requirements to the design solution.

Part IV of the book shifts the focus to address manufacturing systems specifically:

- Chapter 9 provides an AD and an implementation approach for distributed manufacturing systems.
- Chapter 10 seeks to address the multiple competing performance criteria of manufacturing systems. It provides a model for project identification and prioritization.

Finally, the epilogue brings the book to a conclusion. It discusses many of the challenges in designing and implementing large complex systems. It highlights many applications where AD has served to overcome cost overruns and missed project schedules. Together, these 11 chapters serve to demonstrate AD's future role as design science evolves to address the twenty-first century challenges of large complex systems.

Axiomatic Design in Large Systems
Complex Products, Buildings and Manufacturing
Systems

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